

Funkční zobrazování a mapování mozku fMRI

J. Kybic, J. Hirsch¹, J. Hornak², M. Bock, J. Hozman, a další³

2008–2021

¹<http://www.fmri.org>

²<http://www.cis.rit.edu/htbooks/mri/>

³<http://www.biac.duke.edu/education/courses/fall04/fmri/>

Úvod

Motivace a historie

- Anatomie

- Modality pro funkční zobrazování

Aplikace

- Normální mozková aktivita

- Plánování operací

fMRI

- Principy

- Příklad experimentu

Vyhodnocování fMRI dat

- Signál a šum

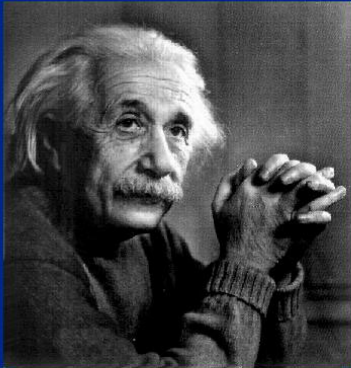
- Lineární model

- Statistické testování

- Návrh experimentu

(f)MRI — závěr

A New View of Brain and Mind: Functional Neuroimaging



Columbia fMRI

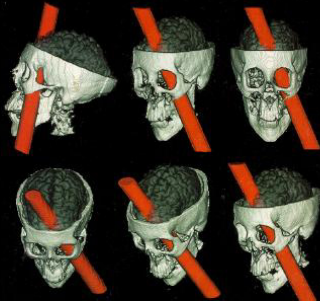


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SCIENCE

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\$6.00



Paul Broca (1861)
Observed language-related
deficits following left frontal
damage to the brain.

Karl Wernicke (1874)
Reported language-related
deficits and motor deficits
following left temporal
damage to the brain.

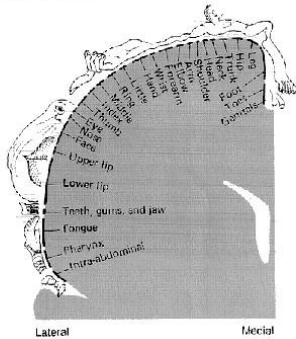
Columbia fMRI



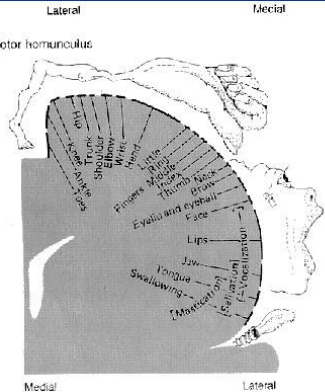
Wilder Penfield
(1937-1954)

Direct Cortical Stimulation

A Sensory homunculus



B Motor homunculus



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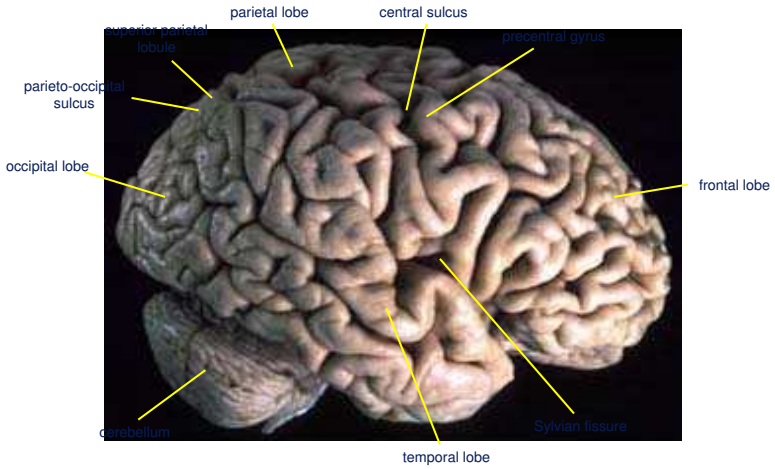
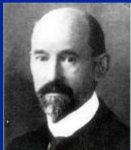
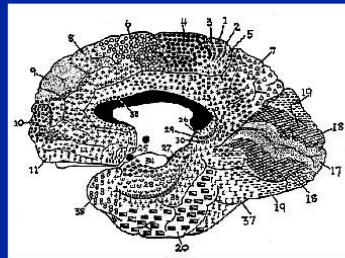
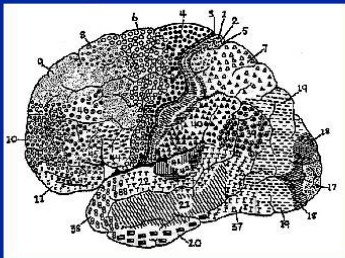


Fig 2.13

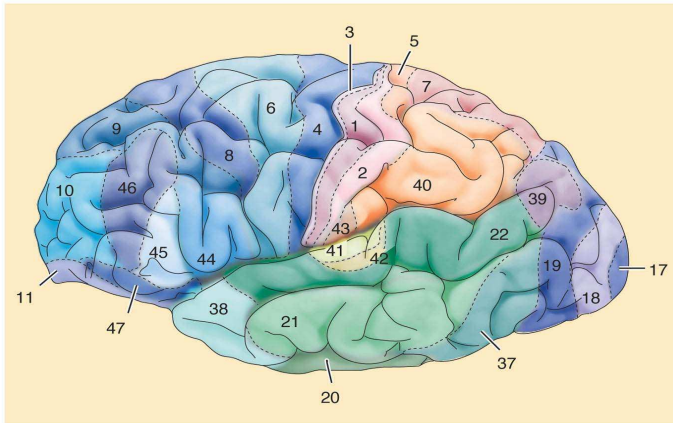
Korbinian
Brodmann 1909



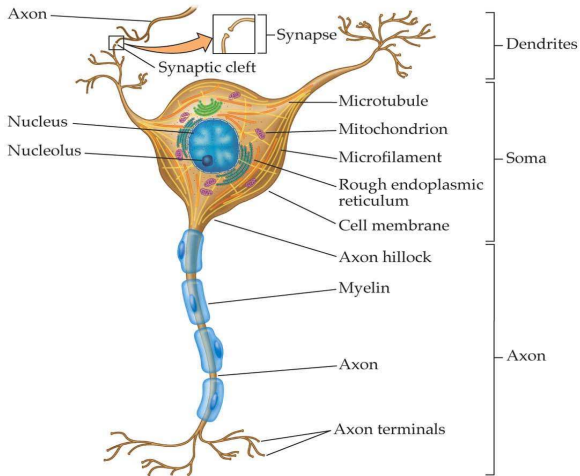
Cortical Cytoarchitecture



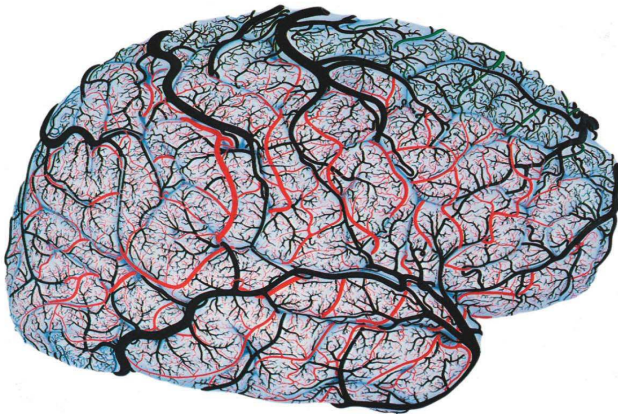
Cytoarchitectonic map, Brodman



Mikrostruktura



Zásobování mozku krví



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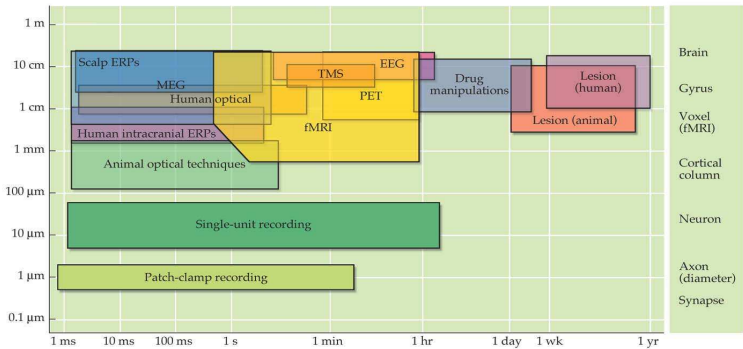
Návrh experimentu

(f)MRI — závěr

Jak lokalizovat funkci mozku

(Shrnutí a připomenutí)

- Invazivní
 - Následky zranění
 - Následky operací
 - Přímá stimulace (dnes jen na zvířatech)
 - Snímací elektrody
 - Optické snímání (při otevřené lebce svítíme laserem, optické vlastnosti se mění s průtokem krve a s elektrickým polem)
- Neinvazivní
 - MEG, EEG
 - fMRI
 - PET



FUNCTIONAL MAGNETIC RESONANCE IMAGING, Figure 1.7 © 2004 Sinauer Associates, Inc.

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Aplikace funkčního mapování mozku

- Porozumění struktuře mozku
- Porozumění procesům vnímání a myšlení
- Nové terapie
 - Porozumění fyziologickým příčinám duševních chorob
 - Porozumění fyziologickým příčinám bolesti a reakci na bolest
 - Porozumění účinkům drog
- Plánování operací
 - Identifikace nefunkčního centra
 - Omezení poškození důležitých center při chirurgické léčbě (epilepsie)

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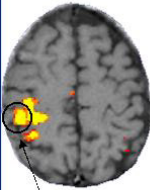
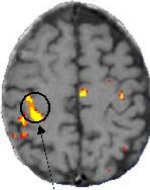
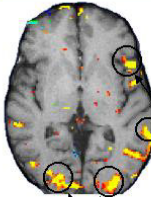
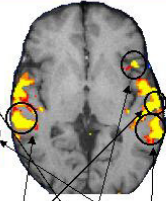
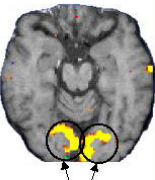
Lineární model

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(f)MRI — závěr

Standard Brain Mapping Tasks

SENSORY	MOTOR	LANGUAGE		VISION
Touch (passive)	Finger Thumb Tapping (active)	Picture Naming (active)	Listening to Words (passive)	Reversing Checkerboard (passive)
				
GPoC	GPrC	GOi	GTT GFi GTs	CaS

From Hirsch, J., et al; Neurosurgery 47: 711-722, 2000



Sensory Motor Mapping

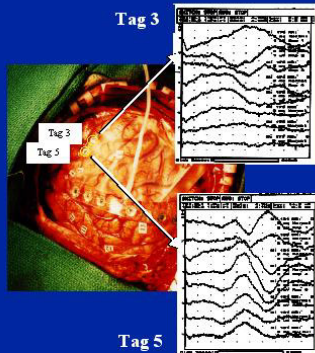
Craniotomy

SSEP

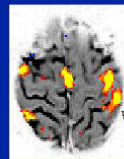
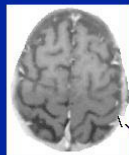
Direct Cortical
Stimulation

Reference
Image

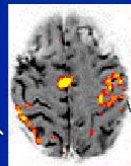
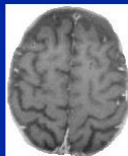
fMRI
Localization



“Twitching of
hand,
focal seizure
involving arm”



“Twitching in
1st three
digits”



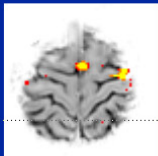
From Hirsch, J., et al; Neurosurgery 47: 711-722, 2000

Columbia fMRI



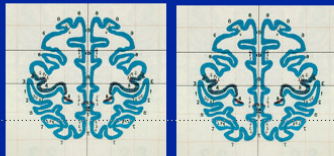
Labeling of Active Brain Areas

Functional Brain



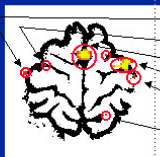
activity

Atlas Brain



labels

transfer



Name	BA	Sector
GPrC	4	c,E
GFs	6	b,E
GFd	6	a,E,60,-a
GFs	6	b,E,60
GRC	4	c,E,60
LPs	7	b,G,60



Co-Planar Stereotaxic Atlas of the Human Brain

Jean Talairach
Pierre Tournoux
Translated by
Mark Rayport

3-Dimensional Proportional System: An Approach to Cerebral Imaging

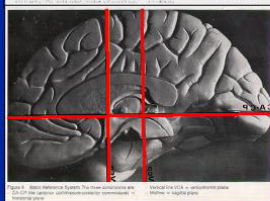
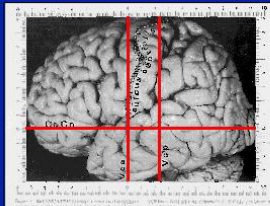
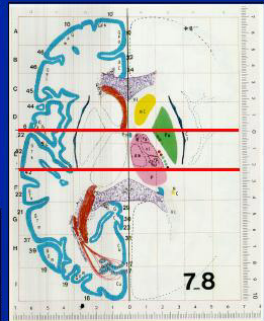
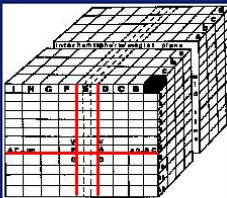
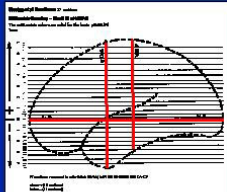
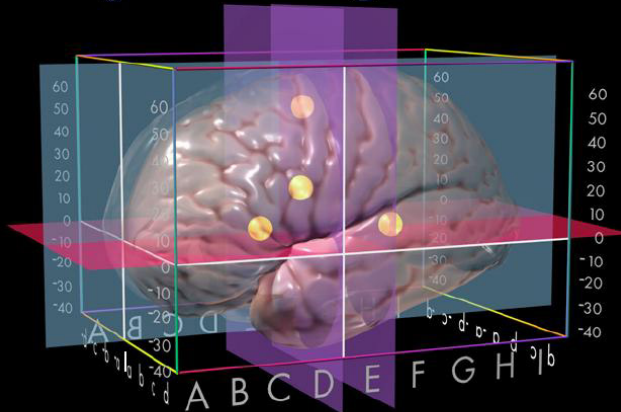


Figure 1. Lateral reference system. The three dimensions are: V.S.P. = vertical plane, A.P. = anterior-posterior, M.P. = medial-lateral.

Figure 2. Medial reference system. The three dimensions are: V.S.P. = vertical plane, A.P. = anterior-posterior, M.P. = medial-lateral.



Object Naming Network



Hirsch, Moreno & Kim, *J. Cognitive Neuroscience*, 13, 1-16, 2001.

Columbia fMRI



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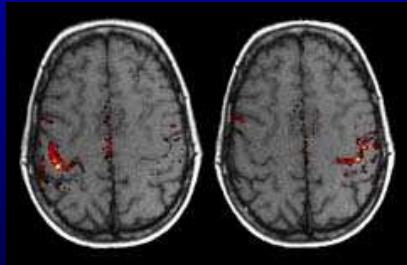
Lineární model

Statistické testování

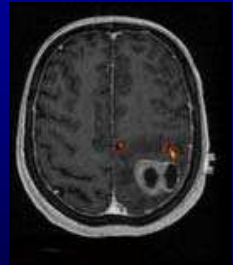
Návrh experimentu

(f)MRI — závěr

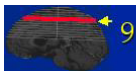
Application: (Neuro)functional MRI



Volunteer



Patient w/ Glioblastoma

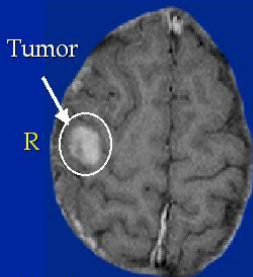


IMAGING

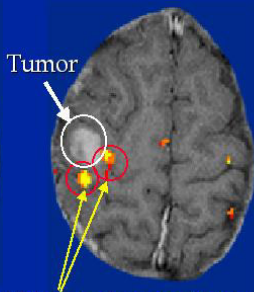
CONVENTIONAL

FUNCTIONAL

AFTER SURGERY



slice 9



Left Hand: Sensory/Motor



Left Hand Movement



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Essential Discoveries that enable PET and fMRI

Angelo Mosso



1881 Observed that blood flow changes were associated with mental activity

1890 Roy and Sherrington described an “intrinsic mechanism by which the vascular supply of the brain can be varied locally in correspondence with local variations in functional activity.”

Linus Pauling



1936 Discovered the Magnetic Properties of Hgb

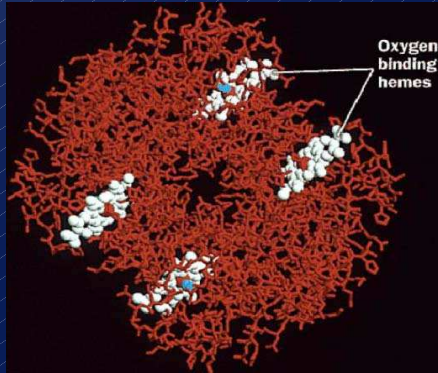
Siege Ogawa



1991 Discovered the Blood Oxygen Level Dependent (BOLD) Signal



Hemoglobin Molecule



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PHYSIOLOGY

NEURAL ACTIVATION
IS ASSOCIATED WITH AN
INCREASE IN BLOOD FLOW

O₂ EXTRACTION IS
RELATIVELY UNCHANGED

RESULT:
REDUCTION IN THE
PROPORTION OF DEOXY HGB
IN THE LOCAL VASCULATURE

PHYSICS

DEOXY HGB
IS PARAMAGNETIC

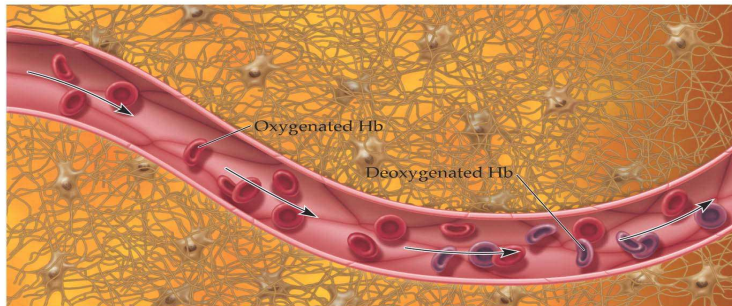
AND DISTORTS THE LOCAL
MAGNETIC FIELD CAUSING
SIGNAL LOSS

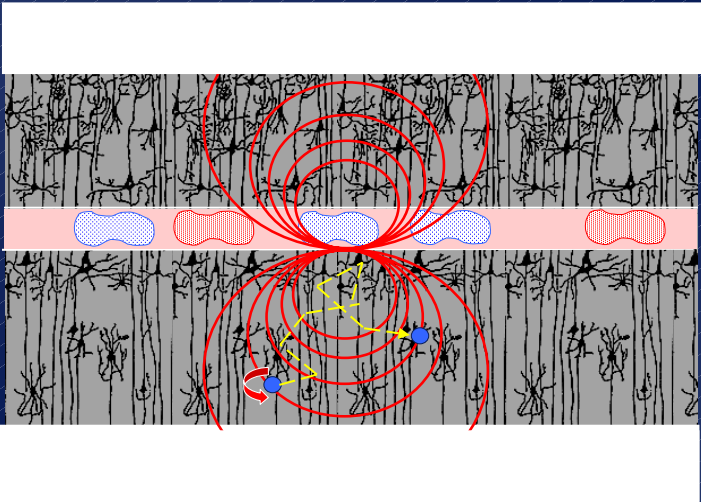
RESULT:
LESS DISTORTION OF THE
MAGNETIC FIELD RESULTS IN
LOCAL SIGNAL INCREASE



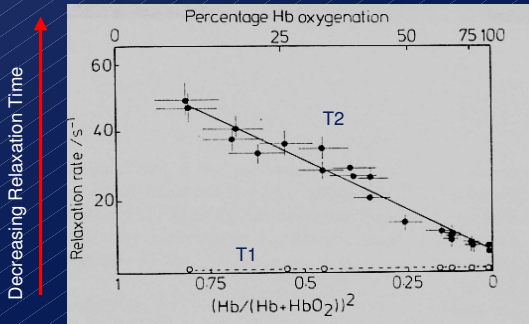
BOLD Signal Generation

(B)





Blood Deoxygenation affects T₂ Recovery



Increasing Blood Oxygenation

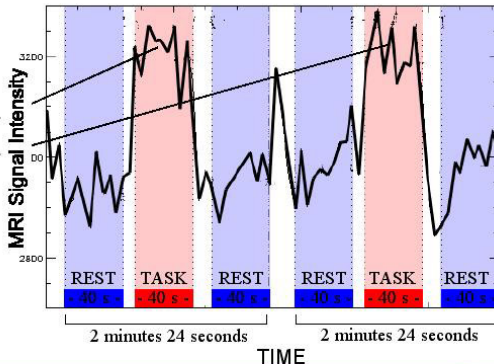
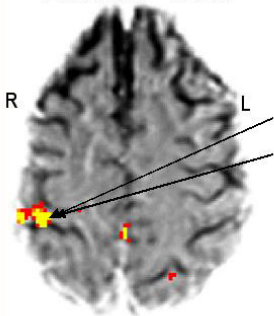
Thulborn et al., 1982

BOLD

- **B**lood **O**xxygen **L**evel **D**ependent
- Gradient echo, EPI (kvůli rychlosti)
- Paramagnetické vlastnosti deoxyhemoglobinu → nehomogenita pole → T_2^* efekt
- Velmi slabý signál (SNR ≈ 0.1)
- Průměrování:
 - Opakujeme např. 10 bloků (snímání) bez aktivity
 - ... 10 bloků (snímání) s aktivitou

Magnetic Resonance Signals to Location of Function

Left Hand - Touch

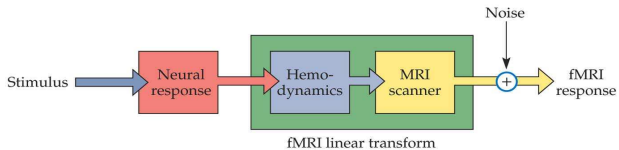


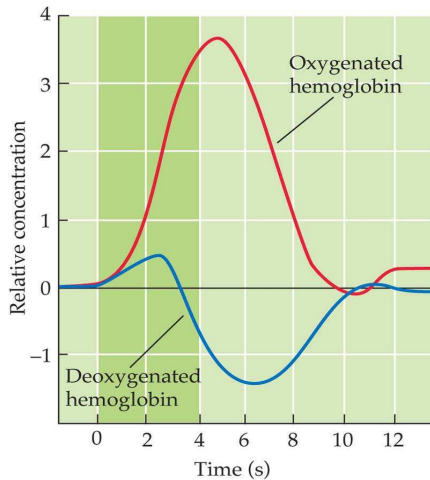
Hemodynamická odezva

Hemodynamic response

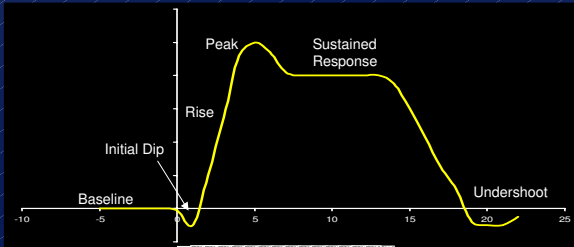
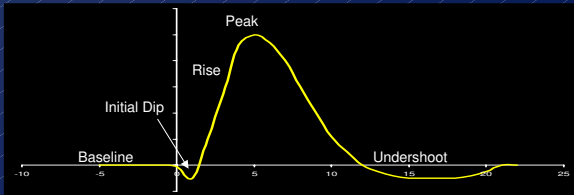
- Nervová aktivita → zásobování krví → BOLD signál
- Reakce není okamžitá, impulzní charakteristika se nazývá **hemodynamická odezva**
- Odezva se liší mezi subjekty i v rámci jednoho subjektu

Hemodynamic response





Basic Form of Hemodynamic Response



Position of Headcoil and Mirror



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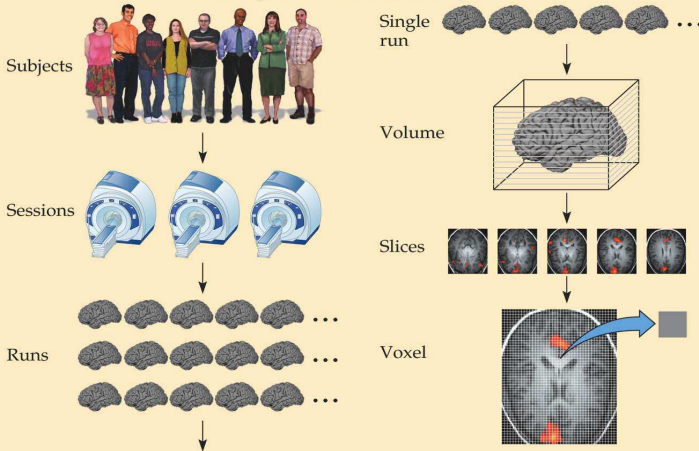
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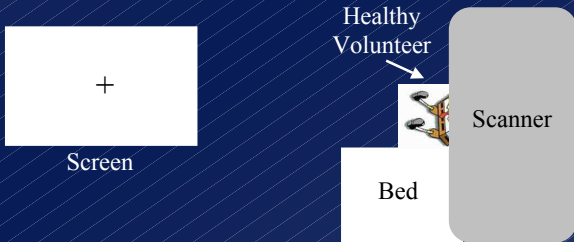
fMRI experimental data hierarchy



The Experiment:

fMRI adaptation of classic PET experiment

- Three Conditions in 21 second epochs
- 1st Condition: Word Generation



The Experiment:

fMRI adaptation of classic PET experiment

- Three Conditions in 21 second epochs
- 1st Condition: Word Generation

Noun is presented

Jellyfish

Screen

Healthy
Volunteer



Bed

Scanner

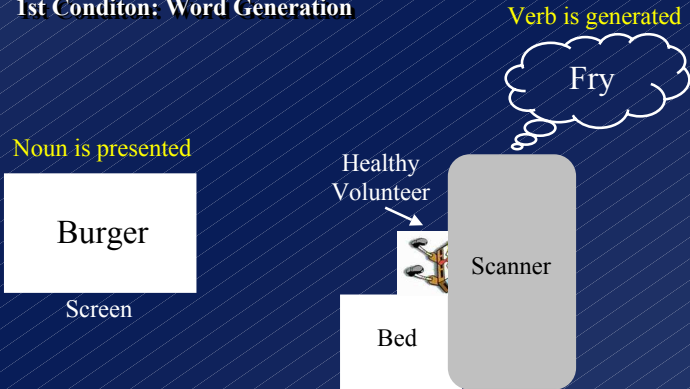
Verb is generated

Catch

The Experiment:

fMRI adaptation of classic PET experiment

- Three Conditions in 21 second epochs
- 1st Condition: Word Generation



The Experiment:

fMRI adaptation of classic PET experiment

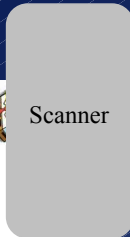
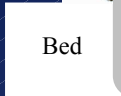
- Three Conditions in 21 second epochs
- 1st Condition: Word Generation
- 2nd Condition: Word Shadowing

Verb is presented



Screen

Healthy
Volunteer



Verb is repeated



The Experiment:

fMRI adaptation of classic PET experiment

- Three Conditions in 21 second epochs
- 1st Condition: Word Generation
- 2nd Condition: Word Shadowing

Verb is presented

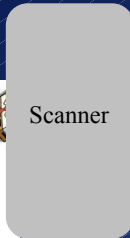


Screen

Healthy
Volunteer



Bed



Scanner

Verb is repeated



The Experiment:

fMRI adaptation of classic PET experiment

- Three Conditions in 21 second epochs
- 1st Condition: Word Generation
- 2nd Condition: Word Shadowing
- 3rd Condition: Baseline

Hair-cross is shown



Screen

Healthy
Volunteer



Scanner

Bed

The Experiment:

fMRI adaptation of classic PET experiment

- Three Conditions in 21 second epochs
- 1st Condition: Word Generation
- 2nd Condition: Word Shadowing
- 3rd Condition: Baseline

Hair-cross is shown



Screen

Healthy
Volunteer



Bed

Scanner

Z
Z
Z
Z
Z
Z
Z
Z
Z
Z
Z

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(f)MRI — závěr

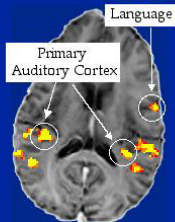
COMPUTATIONS FOR *f*UNCTIONAL IMAGE PROCESSING

Scanner



RECONSTRUCTION
ALIGNMENT
VOXEL BY VOXEL
ANALYSIS
GRAPHICAL
REPRESENTATION

Functional
Brain Map



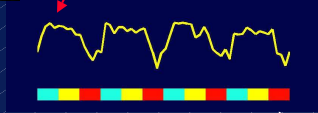
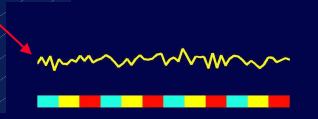
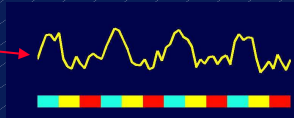
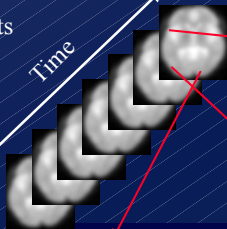
The Data: Set of Volumes or Set of Time-series

Serial Snapshots
of Volunteers
brain

Time



Volunteer

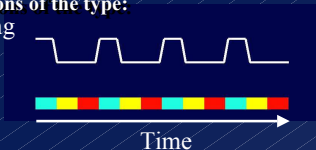


Time

Generation
Shadowing
Baseline

The Model: A Set of Hypothetical Time-series

- A **model** consists of a set of assumptions of the type:
"I think a voxel that is into generating words might have a time-series looking like this"
- and



"A voxel that is into repeating, like this"

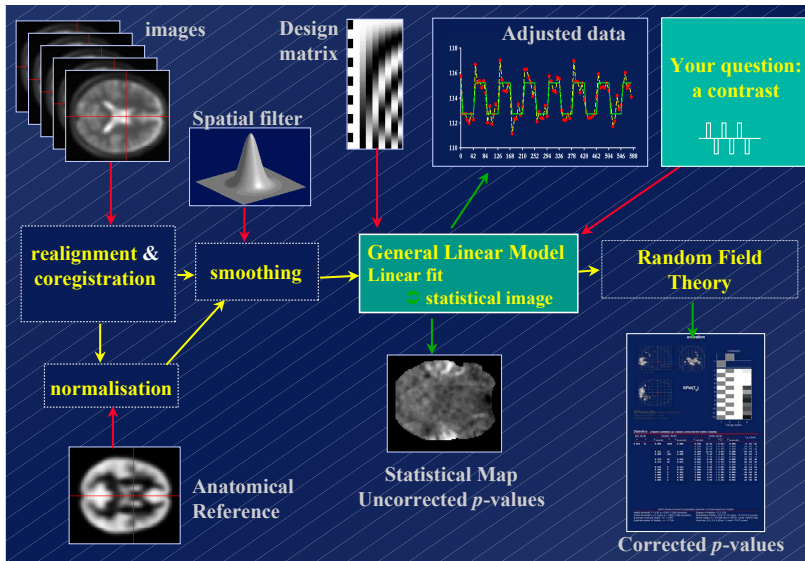


and

"A voxel that just doesn't care, like this"



Generation Shadowing Baseline



Úvod

Motivace a historie

Anatomie

Modality pro funkční zobrazování

Aplikace

Normální mozková aktivita

Plánování operací

fMRI

Principy

Příklad experimentu

Vyhodnocování fMRI dat

Signál a šum

Lineární model

Statistické testování

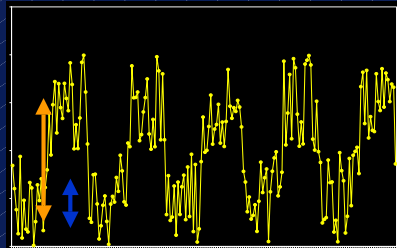
Návrh experimentu

(f)MRI — závěr

Signal-Noise-Ratio (SNR)

**Task-Related
Variability**

**Non-task-related
Variability**



Types of Noise

- **Thermal noise**
 - Responsible for variation in background
 - Eddy currents, scanner heating
- **Power fluctuations**
 - Typically caused by scanner problems
- **Variation in subject cognition**
 - Timing of processes
- **Head motion effects**
- **Physiological changes**
- **Differences across brain regions**
 - Functional differences
 - Large vessel effects
- **Artifact-induced problems**

Variability in Subject Behavior: Issues

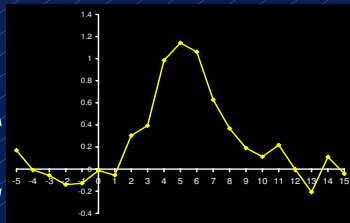
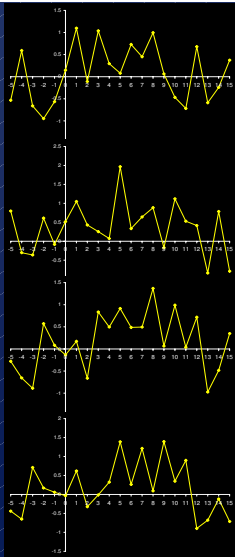
- **Cognitive processes are not static**
 - May take time to engage
 - Often variable across trials
 - Subjects' attention/arousal wax and wane
- **Subjects adopt different strategies**
 - Feedback- or sequence-based
 - Problem-solving methods
- **Subjects engage in non-task cognition**
 - Non-task periods do not have the absence of thinking

What can we do about these problems?

Trial Averaging

- **Static signal, variable noise**
 - Assumes that the MR data recorded on each trial are composed of a signal + (random) noise
- **Effects of averaging**
 - Signal is present on every trial, so it remains constant through averaging
 - Noise randomly varies across trials, so it decreases with averaging
 - Thus, SNR increases with averaging

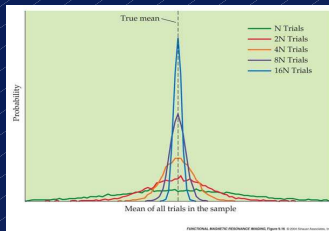
Trial averaging



Average of 16 trials
with SNR = 0.6

Fundamental Rule of SNR

For Gaussian noise, experimental power increases with the square root of the number of observations



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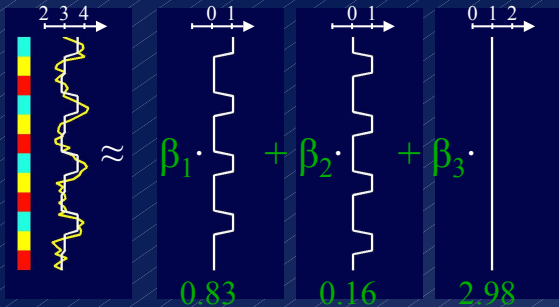
Návrh experimentu

(f)MRI — závěr

The Estimation: Finding the "best" parameter values

- The estimation entails finding the parameter values such that the linear combination "best" fits the data.

Generation Shadowing
Baseline

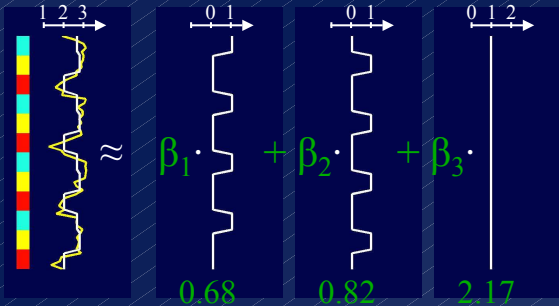


Cool!

The Estimation: Finding the "best" parameter values

- And the nice thing is that the same model fits all the time-series, only with different parameters.

Generation Shadowing Baseline

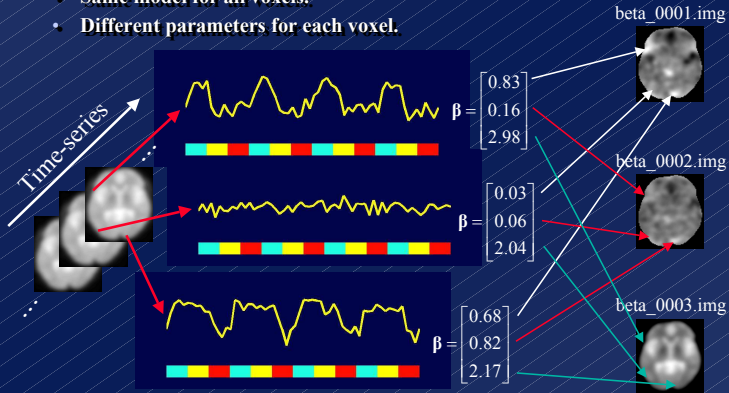


Into words

The Estimation:

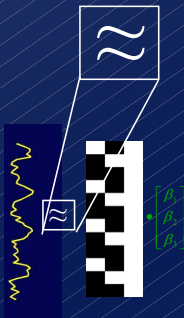
The format of data, model and parameters

- Same model for all voxels.
- Different parameters for each voxel.



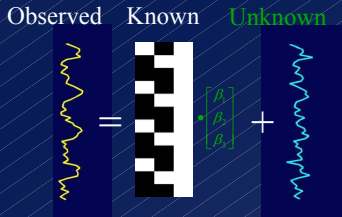
Model revisited – again

Now, what's that
all about?



Remember?

We need a model for the error!



$$y = X\beta + e$$

$$e \sim N(\mathbf{0}, \sigma^2 \mathbf{I})$$

Least squares fit

Model

$$\mathbf{y}_i = X\boldsymbol{\beta}_i + \mathbf{e}_i \quad \text{with noise} \quad \mathbf{e}_i = \mathcal{N}(0, I\sigma_e^2)$$

For each pixel i , calculate the ML estimate

$$\hat{\boldsymbol{\beta}}_i = \arg \min_{\boldsymbol{\beta}_i} \|\mathbf{e}_i\|^2 \quad \text{where residual} \quad \mathbf{e}_i = X\boldsymbol{\beta}_i - \mathbf{y}_i$$

$$\hat{\boldsymbol{\beta}}_i = X^\dagger \mathbf{y}_i = (X^T X)^{-1} X^T \mathbf{y}_i$$

Least squares fit

Model

$$\mathbf{y}_i = X\boldsymbol{\beta}_i + \mathbf{e}_i \quad \text{with noise} \quad \mathbf{e}_i = \mathcal{N}(0, I\sigma_e^2)$$

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$$\hat{\boldsymbol{\beta}}_i = X^\dagger \mathbf{y}_i = (X^T X)^{-1} X^T \mathbf{y}_i$$

Scalar **contrast** (or effect)

$$z_i = \mathbf{c}^T \boldsymbol{\beta}_i$$

pick the coefficient of interest corresponding to the desired activity.

Least squares fit

Model

$$\mathbf{y}_i = X\boldsymbol{\beta}_i + \mathbf{e}_i \quad \text{with noise} \quad \mathbf{e}_i = \mathcal{N}(0, I\sigma_e^2)$$

For each pixel i , calculate the ML estimate

$$\hat{\boldsymbol{\beta}}_i = \arg \min_{\boldsymbol{\beta}_i} \|\mathbf{e}_i\|^2 \quad \text{where residual} \quad \mathbf{e}_i = X\boldsymbol{\beta}_i - \mathbf{y}_i$$

$$\hat{\boldsymbol{\beta}}_i = X^\dagger \mathbf{y}_i = (X^T X)^{-1} X^T \mathbf{y}_i$$

Scalar **contrast** (or effect)

$$z_i = \mathbf{c}^T \boldsymbol{\beta}_i$$

pick the coefficient of interest corresponding to the desired activity.

Variance

$$\sigma_z^2 = \text{Var}(z_i) = \sigma_e^2 \mathbf{c}^T (X^T X)^{-1} \mathbf{c}$$

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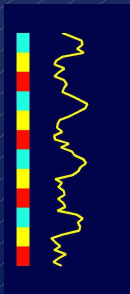
Lineární model

Statistické testování

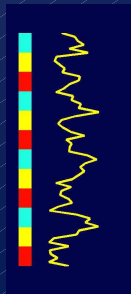
Návrh experimentu

(f)MRI — závěr

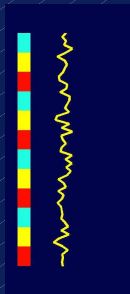
But why do we need the error?
Would you trust these?



$\beta_1=1$
 $\sigma=0.2$
 $n=60$



$\beta_1=1$
 $\sigma=0.5$
 $n=60$



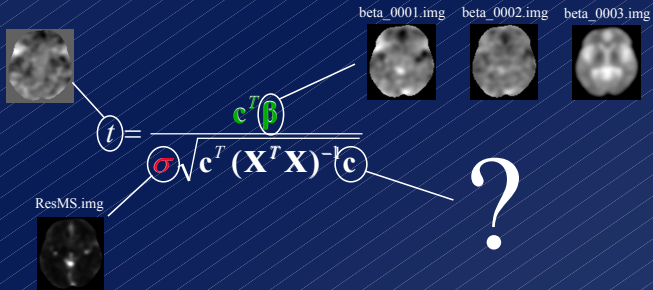
$\beta_1=0.3$
 $\sigma=0.2$
 $n=60$



$\beta_1=1$
 $\sigma=0.2$
 $n=15$

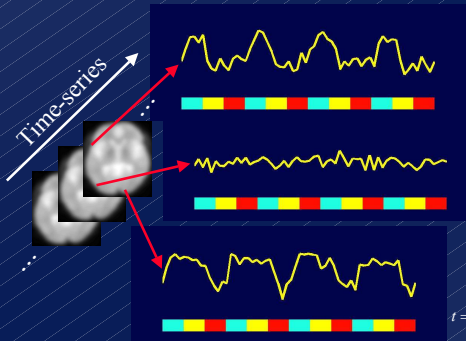
t-test

- We trust: Long series with **large effects** and **small error**.



Asking questions of your data *t*-contrasts

- Can we find voxels that are active in word-generation tasks?

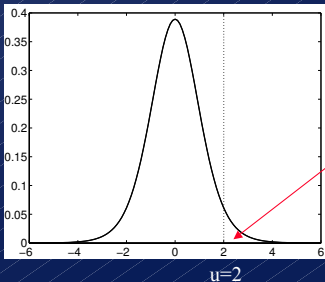


$$t = \frac{\begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0.83 \\ 0.16 \\ 2.98 \end{bmatrix}}{0.41 * 0.32} = \frac{0.83}{0.41 * 0.32} = 6.42^{**}$$

$$t = \frac{\begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0.03 \\ 0.06 \\ 2.04 \end{bmatrix}}{0.19 * 0.32} = \frac{0.03}{0.19 * 0.32} = 0.44$$

$$t = \frac{\begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0.68 \\ 0.82 \\ 2.17 \end{bmatrix}}{0.40 * 0.32} = \frac{0.68}{0.40 * 0.32} = 5.41^{**}$$

Inference at a single voxel



t-distribution

NULL hypothesis, H_0 : activation is zero

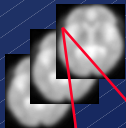
$$\alpha = p(t > u | H_0)$$

p-value: probability of getting a value of t at least as extreme as u . If α is small we reject the null hypothesis.

$$u = (\text{effect size}) / \text{std}(\text{effect size})$$

I'm sorry, can you pose that question differently?

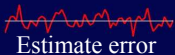
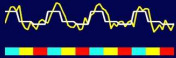
F-contrasts



$$\beta = \begin{bmatrix} 0.83 \\ 0.16 \\ 2.98 \end{bmatrix}$$

Fit model

Get data

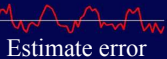
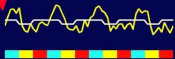


$$t^2 =$$



$$\beta = \begin{bmatrix} -0.25 \\ 3.40 \end{bmatrix}$$

Fit reduced model



$$t^2 =$$

$$F \sim \frac{\text{green bar}}{\text{red bar}} = 41.21$$

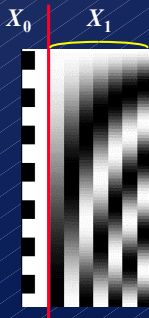
(sort of)

cf.  

F-test (SPM{F}) : a reduced model or ...

Tests multiple linear hypotheses : Does X_1 model anything ?

H_0 : True (reduced) model is X_0



This (full) model ?

X_0



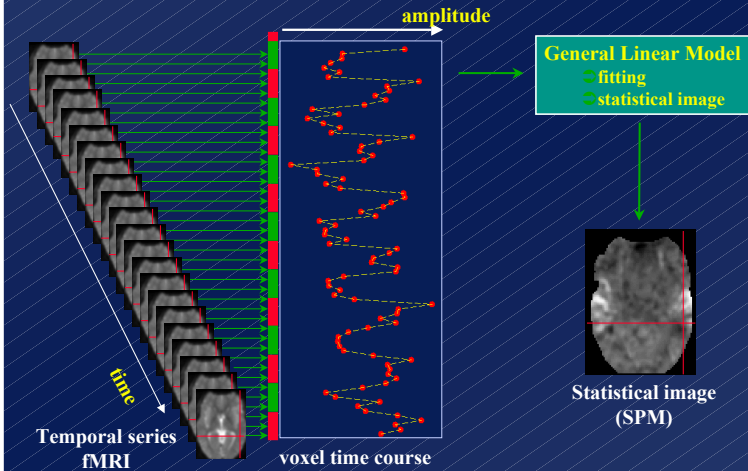
Or this one?

additional
variance
accounted for
by **tested** effects

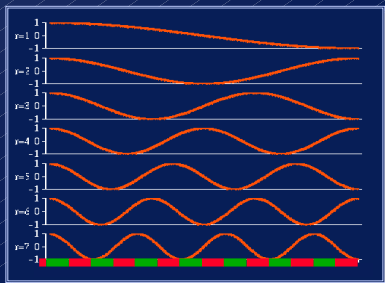
$$F = \frac{\text{additional variance accounted for by tested effects}}{\text{error variance estimate}}$$

$$F \sim (S_0^2 - S^2) / S^2$$

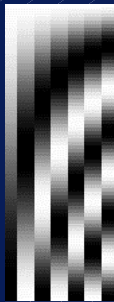
One voxel = One test (t, F, ...)



Add more reference functions ...



Discrete cosine transform basis functions



...design matrix

The diagram illustrates the linear regression equation $Y = X \beta + \epsilon$ with the following components and labels:

- Y : Data vector (represented by a vertical vector of horizontal bars)
- X : design matrix (represented by a vertical matrix of vertical bars)
- β : parameters (represented by a vertical vector of parameters: $\alpha, \mu, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9$)
- ϵ : error vector (represented by a vertical vector of horizontal bars)

The equation is written as $Y = X \beta + \epsilon$. A diagonal label $=$ the betas (here: 1 to 9) points to the parameter vector β .

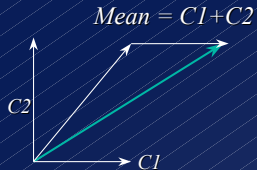
$\hat{\beta}$?

“completely” correlated ...

$$Y = Xb + e$$

$$X = \begin{matrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{matrix}$$

\swarrow \uparrow \swarrow
Cond 1 Cond 2 Mean

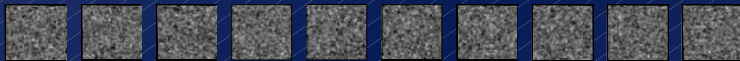


Parameters are **not unique** in general! Some contrasts have no meaning: **NON ESTIMABLE**

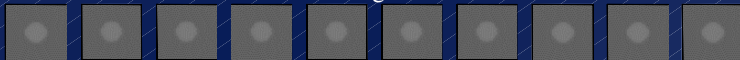
Bonferroni correction

Inference for Images

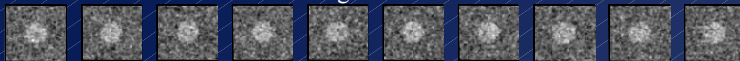
Noise



Signal



Signal+Noise



Use of 'uncorrected' p-value, $\alpha=0.1$



Using an 'uncorrected' p-value of 0.1 will lead us to conclude on average that 10% of voxels are active when they are not.

This is clearly undesirable. To correct for this we can define a null hypothesis for images of statistics.

Family-wise Null Hypothesis

FAMILY-WISE NULL HYPOTHESIS:

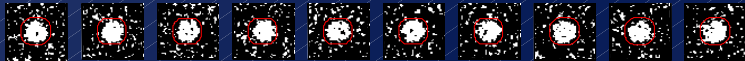
Activation is zero everywhere

If we reject a voxel null hypothesis
at *any* voxel, we reject the family-wise
Null hypothesis

A FP **anywhere** in the image
gives a Family Wise Error (FWE)

Family-Wise Error (FWE) rate = 'corrected' p-value

Use of 'uncorrected' p-value, $\alpha=0.1$



Use of 'corrected' p-value, $\alpha=0.1$



FWE

The Bonferroni correction

The Family-Wise Error rate (FWE), α , for a family of N **independent** voxels is

$$\alpha = Nv$$

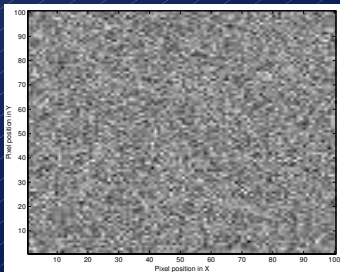
where v is the voxel-wise error rate. Therefore, to ensure a particular FWE set

$$v = \alpha / N$$

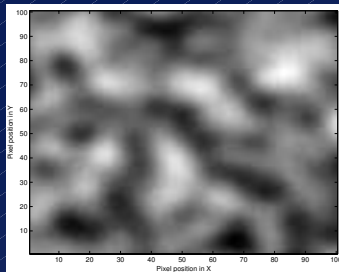
BUT ...

The Bonferroni correction

Independent Voxels



Spatially Correlated Voxels



Bonferroni is too conservative for brain images

Applied Smoothing

Smoothness

smoothness » voxel size

practically

$$FWHM \geq 3 \times \text{VoxDim}$$

Typical applied smoothing:

Single Subj fMRI: 6mm

PET: 12mm

Multi Subj fMRI: 8-12mm

PET: 16mm

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(f)MRI — závěr

fMRI Design Types

- 1) Blocked Designs**
- 2) Event-Related Designs**
 - a) Periodic Single Trial**
 - b) Jittered Single Trial**
 - c) Staggered or Interleaved Single Trial**
- 3) Mixed Designs**
 - a) Combination blocked/event-related**
 - b) Variable stimulus probability**

What are Blocked Designs?

- **Blocked designs segregate different cognitive processes into distinct time periods**



Refractory Periods

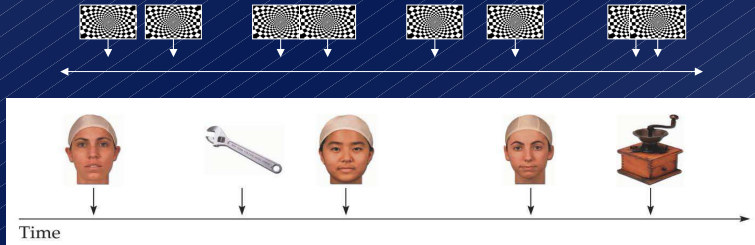
- **Definition: a change in the responsiveness to an event based upon the presence or absence of a similar preceding event**
 - **Neuronal refractory period**
 - **Vascular refractory period**

Limitations of Blocked Designs

- **Very sensitive to signal drift**
 - Sensitive to head motion, especially when only a few blocks are used.
- **Poor choice of baseline may preclude meaningful conclusions**
- **Many tasks cannot be conducted repeatedly**
- **Difficult to estimate the HDR**

What are Event-Related Designs?

- **Event-related designs associate brain processes with discrete events, which may occur at any point in the scanning session.**

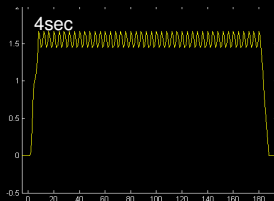
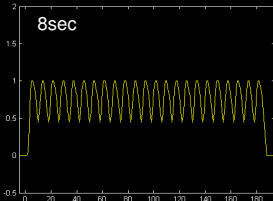
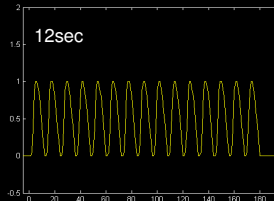
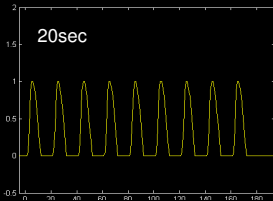


2a. Periodic Single Trial Designs

- Stimulus events presented infrequently with long interstimulus intervals



Trial Spacing Effects: Periodic Designs

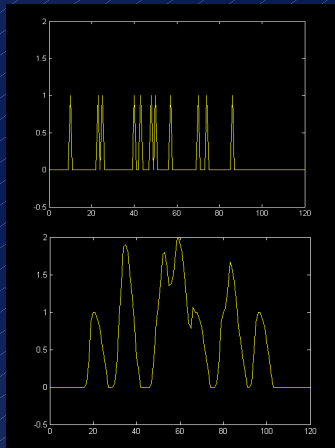
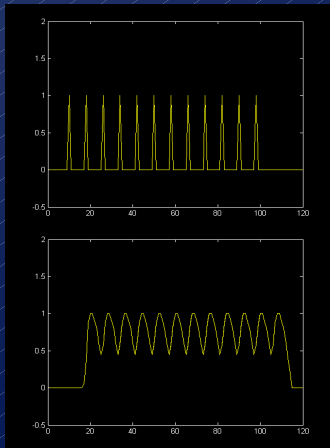


2b. Jittered Single Trial Designs

- Varying the timing of trials within a run
- Varying the timing of events within a trial



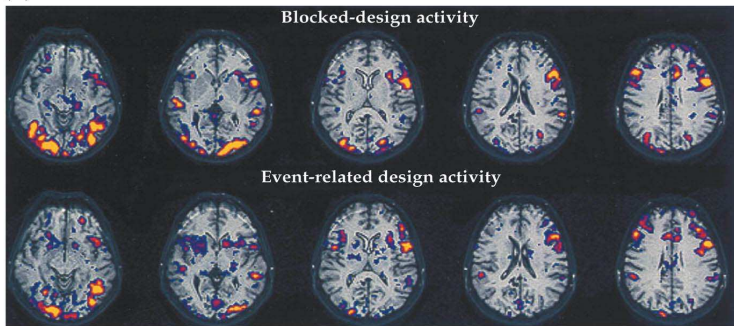
Effects of Jittering on Stimulus Variance



Limitations of Event-Related Designs

- **Differential effects of interstimulus interval**
 - Long intervals do not optimally increase stimulus variance
 - Short intervals may result in refractory effects
- **Detection ability dependent on form of HDR**
- **Length of “event” may not be known**

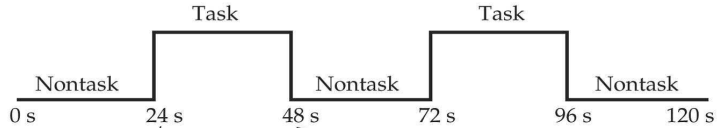
(A)



Word-stem completion task. Blocked design: 30s on/off. Event-related design: 15s ISI.

3a. Combination Blocked/Event

- **Both blocked and event-related design aspects are used (for different purposes)**
 - Blocked design is used to evaluate *state-dependent* effects
 - Event-related design is used to evaluate *item-related* effects
- **Analyses are conducted largely independently between the two measures**
 - Cognitive processes are assumed to be independent

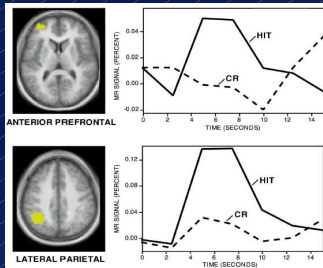
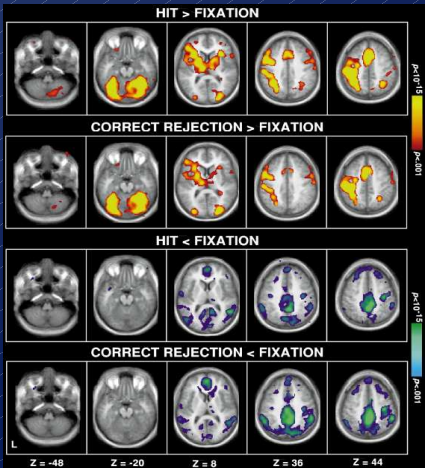


Post-hoc sorting

Dodatečné třídění

- Rozhodneme se až dodatečně (podle výsledku experimentu), do které kategorie pokus zařadíme.
- **Typický příklad:** Subjekt odpověděl správně/špatně.

Post-Hoc Sorting of Trials



Data from old/new episodic memory test.

From Konishi, et al., 2000

Úvod

Motivace a historie

Anatomie

Modality pro funkční zobrazování

Aplikace

Normální mozková aktivita

Plánování operací

fMRI

Principy

Příklad experimentu

Vyhodnocování fMRI dat

Signál a šum

Lineární model

Statistické testování

Návrh experimentu

(f)MRI — závěr

MRI — závěr

- ⊕ 3D zobrazování
- ⊕ Výborné prostorové rozlišení
- ⊕ Neinvazivní
- ⊕ Obrovská variabilita — nejuniverzálnější ze zobrazovacích technik

MRI — závěr

- ⊕ 3D zobrazování
- ⊕ Výborné prostorové rozlišení
- ⊕ Neinvazivní
- ⊕ Obrovská variabilita — nejuniverzálnější ze zobrazovacích technik
- ⊖ Cena
- ⊖ Silná (elektro)magnetická pole — opatrnost nutná
- ⊖ Nepohodlí — hluk, stísněný prostor

fMRI — závěr

- ⊕ Lze zjistit, kde mozek pracuje
- ⊕ In-vivo
- ⊕ Neinvazivní
- ⊕ Relativně dobré prostorové rozlišení
- ⊖ Špatné časové rozlišení
- ⊖ Nutnost průměrování (nelze snímat ojedinělé jevy)